



# Evidence for reduced environmental variability in response to increasing human population growth during the late Holocene in northwest Tasmania, Australia

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## ABSTRACT

A fundamental tenet of human land management is to create spatial and temporal predictability in an environment to improve subsistence. Detecting the relationship between humans and their environment in the palaeo-record is confounded by a number of factors, not the least of which is an adequate pairing of the scales of both the palaeoecological and archaeological records. We aimed to determine the impact, if any, of Aboriginal occupation on the environment surrounding an occupation site in northwest Tasmania, Australia. We analysed the sediments within two small wetlands in northwest Tasmania for pollen, charcoal and loss-on-ignition: (1) a high intensity occupation site –with direct evidence of human occupation; and (2) a low intensity occupation site –with no direct evidence of human occupation. Fire activity and environmental variability covaried at both sites in response to regional climatic change, except between ca. 1700–900 cal yr BP. This period is synchronous with peak human population growth in the region derived from statistical manipulation of the regional (northwest Tasmanian) archaeological dataset. During this period, the high intensity occupation site experienced a peak in fire activity along with a marked reduction in the rate-of-change, reflecting a phase of low variability at a time of increased climatic variability and peak human population growth, while the low intensity occupation site maintained the positive relationship between fire activity, and climatic and environmental variability experienced by both sites at other times. We contend that increased human occupation intensity between ca. 1700 to 900 cal yr BP led to an increased intensity of land management and a resultant decrease in environmental variability as people actively managed the landscape to create a stable and predictable environment.

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## 1. Introduction

As we currently grapple with rapid and widespread global environmental and climatic changes and strive to achieve the global imperative of sustainability (Goodland, 1998; Dearing et al., 2008; Seddon et al., 2014), it is fundamental that we understand human-environment interactions over time so that we can fully appreciate how and why our activities influence environmental systems. This is particularly important for landscapes recently colonised by Europeans in which imported landscape management paradigms have resulted in widespread environmental degradation (Bradshaw, 2012). In Australia, for example, the impact that

Aboriginal people on the environment remains a contentious topic with several conflicting hypotheses that range from benign opportunism to wilful mastery (e.g. Horton, 1982; Bowman, 1998; Langton, 1998; Gammage, 2011). The recent increase in catastrophic landscape-scale fires in Australia (Sharples et al., 2016) has been attributed, in part, to the disruption of millennia of fire manipulation by indigenous Australians to manage their landscapes (Marsden-Smedley, 1998; Russell-Smith et al., 2003; Attiwill and Adams, 2013). Thus, understanding how Aboriginal people influenced Australian landscape evolution is important, not only for informing debates about past fire practices but, for managing the landscape systematically, skilfully and sustainably (Russell-Smith et al., 1997; Hill et al., 1999; Marsden-Smedley and Kirkpatrick, 2000; Yibarbuk et al., 2001; Scherjon et al., 2015). Interdisciplinary approaches to understanding long-term human-environment interactions that combine palaeoecology and archaeology

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have the potential to provide key insights into the historical legacy of humans on landscapes and how inhabited landscapes have evolved in concert with humans. Here, we compare high resolution palaeoecological data with archaeological data and archives of climatic change in an attempt to understand long-term human environment interactions in northwest Tasmania, Australia, a region with evidence for a long history of human occupation, but from where there is a dearth of complementary palaeoenvironmental data.

A fundamental tenet of land management is to create spatial and temporal predictability in an environment to improve subsistence. Modern humans first colonised Australia at least 60–70,000 years ago (60–70,000 cal yr BP) (Clarkson et al., 2017), with the continental island of Tasmania first settled by ca. 38,000 cal yr BP (Cosgrove, 1999). The principal tool with which Aboriginal people have managed the Australian environment throughout this time is fire. The rationale for use of fire as a landscape management tool is straightforward and evident across most cultures in the world (Scherjon et al., 2015): fires are used to promote fresh, new plant growth to attract game (to then hunt), to create open passages to traverse, to promote plant foods, and to protect areas of occupation (Head, 1994; Russell-Smith et al., 1997; Langton, 1998; Yibarbuk et al., 2001; Whitehead et al., 2003; Bliege-Bird et al., 2008, 2013; Scherjon et al., 2015). The central role of fine-scale Aboriginal mosaic burning in the evolution of the Australian landscape is evident from the radical transformation of the Australian landscape following British invasion in the 18th century and the subsequent cessation of traditional fire management over much of the continent (Gammage, 2011). Outside areas cleared for farmland and other colonial purposes, this shift in fire regime resulted in widespread woody encroachment of open landscapes (e.g. Lunt, 1998; Gammage, 2011), and a subsequent increase in landscape-scale fires that are associated with species extinctions and biodiversity loss (Marsden-Smedley, 1998; Bradstock et al., 2002; Bird et al., 2008; Holz et al., 2015). While these changes reveal a profound influence of Aboriginal people over the Australian landscape, such evidence remains elusive and much debated in the palaeoenvironmental record (Bowman et al., 2016).

Understanding human-environment interactions has emerged as a prominent research agenda within both archaeology and palaeoecology (e.g. Anderson et al., 2006; Dearing, 2006; Costanza et al., 2007; Cooper and Peros, 2010; Kintigh et al., 2014; Seddon et al., 2014a; Holmgren et al., 2016; Fernández-López de Pablo et al., 2018). Palaeoenvironmental research has demonstrated the important role that climate has in determining the development and distribution of ecosystems, however the impact of humans on ecosystems and of environmental change on humans remains contentious, particularly when studies of environmental change are conducted in isolation from archaeology (Coombes and Barber, 2005; Briggs et al., 2006; Munoz et al., 2010; Caseldine and Turney, 2010). While integrated studies of environmental and archaeological changes can provide valuable insights into human-environment interactions (Dearing et al., 2006; Dearing, 2006; England et al., 2008; Munoz et al., 2010), such insights are often limited by the varying temporal and spatial scales represented by palaeoecological and archaeological data (Thomas, 1993; Cooper and Peros, 2010). A case in point is the attribution of broad-scale (regional or continental-scale) environmental and climatic changes to understanding trends in site-based archaeological data (e.g. Cosgrove et al., 1990; Cosgrove, 1999; Hiscock, 2002, 2006; Genever et al., 2003; Bickford and Gell, 2005; Holdaway and Fanning, 2010).

Despite the longevity of occupation, ascertaining the influence of Aboriginal people on the Australian environment remains challenging. This elusiveness stems from, among a range of

confounding factors, (1) the central role fire plays in Australian landscape dynamics irrespective of humans, (2) the paucity of coupled and appropriately scaled palaeoenvironmental and archaeological records, and (3) the insensitivity of many palaeoecological sites and proxies (eg. poor pollen taxonomic resolution) to the fine-scale environmental change associated with Aboriginal land management with fire. Here, we present two high-resolution records of fire (charcoal), vegetation (pollen) and wetland sedimentary changes (loss-on-ignition) spanning the last ca. 6000 years from northwest Tasmania, Australia. We attempt to mitigate some of the confounding factors inherent in coupled palaeoecological-archaeological studies in Australia by selecting two small wetland sites that record local-scale environmental change in northwest Tasmania, Australia: one that is adjacent to a known human occupation site and a valuable spongelite quarry – a high intensity occupation site; and one at which there is no direct evidence of human occupation – a low to no intensity occupation site. The study area is recognised as a cultural landscape created by millennia of Aboriginal land management with fire: the Western Tasmanian Aboriginal Cultural Landscape. We compare our environmental data with a reanalysis of the existing local (northwest Tasmanian) archaeological record and with data recording regional climatic change in an attempt to understand effects of fire, climate and people on long-term environmental change in the study area. We hypothesise that the response of the local environment around high intensity human occupation sites to changes in climate will differ from areas of low to no human occupation intensity. We further hypothesise that an increase in the intensity of human occupation will result in reduced local-scale environmental variability around high intensity occupation sites, relative to low occupation intensity sites, as people attempt to create a stable and predictable environment in which they live. Increased occupation of an area would, presumably, increase resource demands, prompting more intense and/or targeted, management effort in order to secure resources. More frequent/targeted burning, for example, would promote young shoot formation that would attract and retain game, while increased occupation would also carry with it social responsibilities of country keeping that are principally carried out using fire in Australian indigenous societies. The net result of increased occupation intensity, then, would be a more predictable and profitable landscape in response to increased anthropogenic burning.

## 2. The study region

### 2.1. Northwest Tasmania

Tasmania (41–44°S and 144–149°E) is a large continental island, intermittently separated from southeast Australia by the Bass Strait (a shallow sea ca. 120 m deep). Northwest Tasmania (40°S and 144°E) consists predominantly of low-lying areas, with a Pleistocene interglacial coastline extending up to 15 km inland. The low plateaus host restricted areas of rainforest, wet-sclerophyll (*Eucalyptus* spp.) forests interspersed with *Acacia* spp. and areas of swamp forest dominated by *Melaleuca* and *Leptospermum* species (Kitchener and Harris, 2013). Coastal margins host extensive areas of sedge- and heathlands (comprised of *Banksia marginata*, *Sprengelia incarnata*, *Amperea xiphoclada*, *Epacris* spp.), *Leptospermum* spp. scrub, *Melaleuca* spp. swamp-forests (*Melaleuca* spp. and *Acacia* spp.) and native grasslands (Kitchener and Harris, 2013). The climate is temperate maritime with mild winters and cool summers. Precipitation decreases northwards, with average annual rainfall decreasing from 2000 mm in the south to 600 mm in the north. Average daily temperatures range from 6 °C to 24 °C annually. Inter-annual precipitation variability in Tasmania is

driven by changes both the El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Garreaud et al., 2009; Hill et al., 2009; Risbey et al., 2009). El Niño events are associated with less precipitation over the north and east of Tasmania (Mariani et al., 2016), while SAM-related rainfall changes occur predominantly in the west and southwest (Mariani and Fletcher, 2016). Changes in fire activity in Tasmania are governed by changes in climate, with increased fire occurrence during El Niño events in the north and east of Tasmania, and increased fire occurrence associated with positive phases of SAM determined fire activity in the west and south (Mariani and Fletcher, 2016; Mariani et al., 2016). Northwest Tasmania is positioned at the interface of the modern zones of influence of SAM and ENSO in Tasmania (Fig. 1).

## 2.2. Human history in northwest Tasmania

Archaeological evidence for occupation on islands to the north of northwest of Tasmania indicates a presence in the region for at least 23,000 years (Bowdler, 1974, 1988, 2015). Direct evidence of occupation of the northwest Tasmanian coastline occurs only after ca. 4000 cal yr BP, following the establishment of the modern sea-level, with most sites being occupied after ca. 1500 cal yr BP (Jones, 1966; Ranson, 1978; Stockton, 1981) (Fig. 1). Jones (1981) suggested that northwestern Tasmanian sites served three economic roles: (1) as a base for tribes to collect food; (2) seasonal occupation to raid seal colonies; and (3) as stopping places for groups during their seasonal movements. Excavations at *Nungu* (West Point), a large coastal midden on the northwest coast,

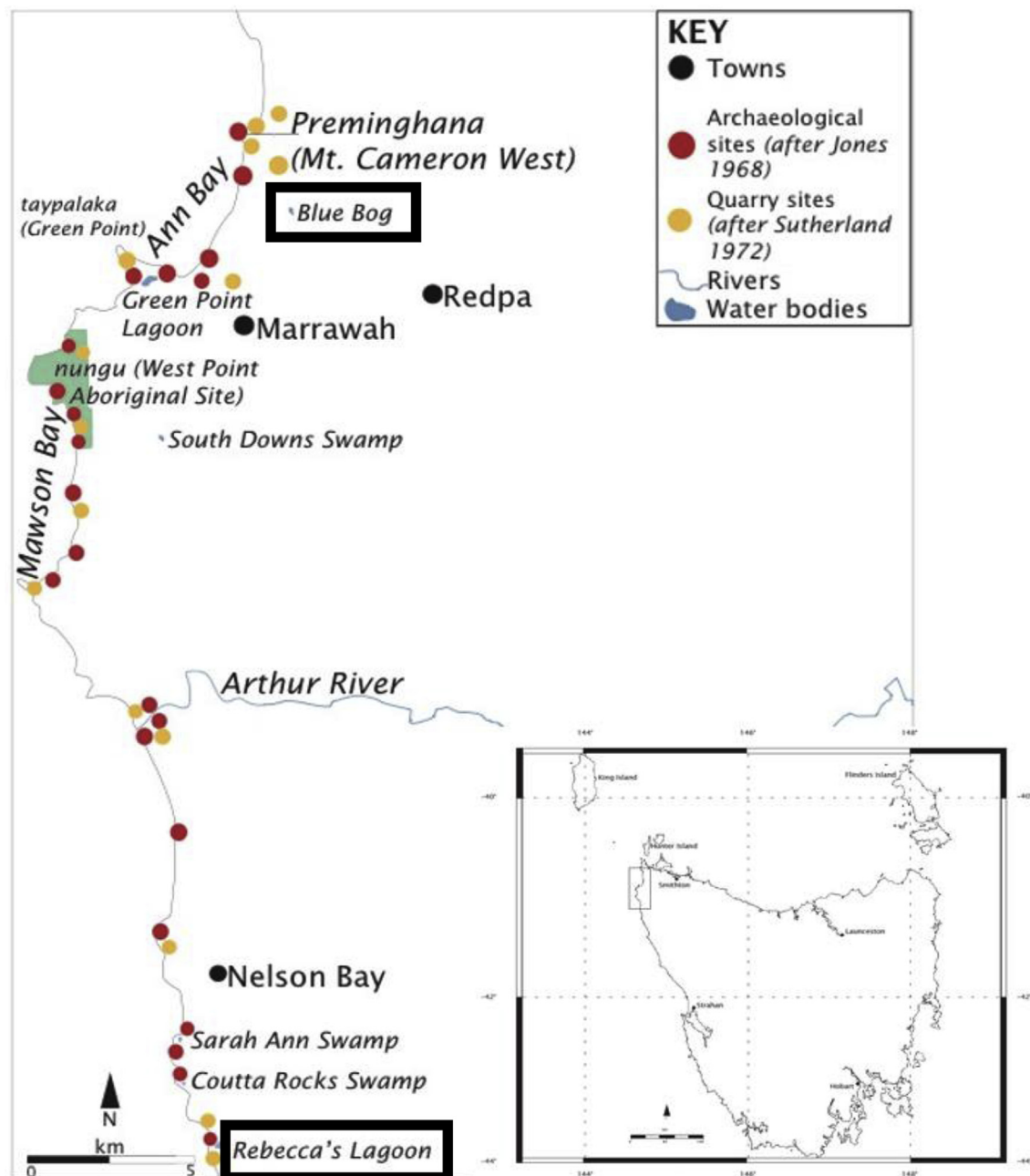


Fig. 1. Composite map of study sites and archaeological sites within the region. The core sites (Blue Bog and Rebecca Lagoon) are highlighted in black rectangles.

demonstrate occupation by a sophisticated and complex society between ca. 2000 cal yr BP and the British invasion (ca. 1803 CE). During this time, people harvested shellfish from the intertidal zone, heavily exploiting Southern Elephant Seals (*Mirounga leonina*), as well as continually harvesting land mammals and birds (Jones, 1966, 1967, 1981). In addition to resource harvesting, the people of West Point manufactured stone tools from local quarries of spongelite, quartzite and basalt (Jones, 1966, 1981). They also engaged in complex ceremonial burials (people adorned with the foot bones of wallabies, the claws of a hawk and >30 shells, each pierced with a circular hole) and cremation of their dead (Jones, 1966).

### 2.3. Study sites

#### 2.3.1. Blue Bog (low occupation intensity)

Blue Bog (40°53'47.40"S, 144°43'14"E) is a shallow inland swamp at 33 m above sea level (asl), 2.5 km from the present coastline and, despite comprehensive archaeological surveys of the region, not proximal to any known archaeological material (Fig. 1). The swamp is ca. 3825 m<sup>2</sup> in size, with two narrow streams flowing from the north with no obvious outflow, overlying Quaternary coastal sands and gravels (Calver et al., 2011). Annual average precipitation at the Marrawah climate station in northwest Tasmania (40°55'14"S, 144°42'59"E; 110 m asl; 3.3 km south-west of Blue Bog) is ca. 1074 mm, with May–September as the wettest months averaging 120 mm of precipitation. The local vegetation is a very dense (near impenetrable) swamp-forest complex of *Leptospermum* spp. with tall shrubs with *Juncus pallidus* growing in the swamp and *Eurychora complanata* near the inlets. Surrounding the swamp is *Eucalyptus* spp. forest, with a very thick understorey of *Acacia melanoxylon*, *A. dealbata*, *Exocarpus cupressiformis*, *Lomatia tinctoria*, *Monotoca glauca* and *Dodonaea* spp. Ground cover, where apparent, is predominantly *Pteridium esculentum* and *Gahnia grandis*.

#### 2.3.2. Rebecca Lagoon (high occupation intensity)

Rebecca Lagoon (41°11' 28"S, 144°41'42"E) is a shallow (1 m deep), freshwater, pH neutral coastal lagoon located 220 m from the present coastline (Saunders et al., 2012) (Fig. 1). The lagoon is ca. 140,000 m<sup>2</sup> in size, lies 8 m asl and overlies Quaternary coastal sands and gravel deposits, with shallow marine to peritidal silt-stones underlying the catchment and surrounding area (Calver et al., 2011). A narrow inlet flows in from the north-west with no outlet. Annual average precipitation at the Temma climate station in northwest Tasmania (41°13'42"S, 144°41'25"E; 7 m asl; 4 km south of Rebecca Lagoon) is ca. 1057 mm, with May–September as the wettest months averaging 186 mm of precipitation. The local catchment supports swamp-forest vegetation comprised of *Melaleuca* spp. and *Leptospermum* spp. shrubs and small trees with the greater area mostly cleared for agriculture since ca. 1830s CE (Julen, 1974). Along the banks of the lagoon, *Eurychora complanata* and *Baumea* spp. are common particularly along the southern margin, with an abundance of *Myriophyllum* spp. growing in the lagoon.

The lagoon is located behind a large dune field (ca. 1.5 km long and 17 m asl) that hosts extensive shell middens containing an abundance of *Turbo* spp. and *Abalone* spp. and stone artefacts manufactured on quartz, quartzite, basalt, black chert and spongelite. A number of hut depressions are evident near the top of the dune and in proximity to Rebecca Creek. Rebecca Lagoon hosts a number of economically important resources, including swans, water ribbon tubers (*Triglochin* spp.), water chestnut (*Eleocharis sphacelata*), yam-daisies (*Microseris scapigera*) and native spinach (*Actites megalocarpa*) (Gott, 1982a; b; 1983, 1999; 2005; Hope, 1999). Outcrops of spongelite about Rebecca Creek and are within

3 km of the lagoon. The sand dune supports low-lying coastal vegetation comprised mostly of *Spinifex sericeus* with some occurrences of *Carpobrotus rosii* and low *Acacia* spp. shrubs.

### 3. Material and methods

#### 3.1. Coring and core chronology

A D-Section (Russian) corer was used to recover sediments from Blue Bog, while a Universal Corer was used at Rebecca Lagoon (Aquatic Research Instruments, 2006). Sediment was described in detail using Munsell colours (Munsell Color, 2009) and a revised version of the Troels-Smith method (Kershaw, 1997), and subsequently subsampled at 1-cm intervals for Blue Bog (TAS1602) and 0.5-cm intervals for Rebecca Lagoon (TAS10606SC2). Samples for <sup>14</sup>C (4 for Blue Bog and 6 for Rebecca Lagoon) were based on bulk samples or on macrofossils when available. Accelerated Mass Spectroscopy (AMS) dating of samples was conducted at Direct AMS laboratory in Bothell, Washington, USA. Ages were calibrated using the Southern Hemisphere calibration curve (SHCal13) (Hogg et al., 2013). Age-depth modelling was performed using BACON (v2.2) (Blaauw and Christen, 2011; R Core Development Team, 2016).

#### 3.2. Charcoal analysis

Contiguous sub-samples of 1.25 cm<sup>3</sup> were taken every 1-cm for Blue Bog (TAS1602) and 0.5-cm for Rebecca Lagoon (TAS10606SC2) for macroscopic charcoal analysis using standard methods: samples were treated with 10% Hydrogen peroxide for 1 week to digest non-charcoal organic matter (Whitlock and Larsen, 2002). Digested samples were washed through a 250 µm and 125 µm sieves and tallied under an Olympus SZ51 dissecting microscope. Macroscopic charcoal values were summed and presented as particles of charcoal per unit of volume of sediment per year (CHAR particles per cm<sup>2</sup> per year), calculated from the methods outlined in Higuera et al. (2010). Microscopic charcoal was counted alongside pollen, counting all charred particles >5 µm. Accumulation rates were calculated for the microscopic charcoal fragments by dividing concentration values (calculated by adding a *Lycopodium* spp. spike) (Stockmarr, 1971) by deposition time (yr cm<sup>-1</sup>).

#### 3.3. Pollen analysis

Processing of pollen samples followed standard methods based on modified procedures outlined in Faegri and Iverson (1989) with the addition of exotic *Lycopodium* spp. spores (Stockmarr, 1971) to calculate the accumulation of subfossils. Sub-samples of 0.5 cm<sup>3</sup> were taken every 2 cm for both cores and additional sub-samples of 0.5 cm<sup>3</sup> were taken at intervals of points of interest. A minimum of 300 terrestrial pollen grains (excluding terrestrial fern spores taxa and algal cysts) were counted. *Melaleuca* spp. was excluded from the terrestrial subtotal for Blue Bog due to high count values. Pollen counting was undertaken at X400 and X630 magnification. Pollen and spore counts were converted into percentages and presented in a pollen diagram using the TILIA and TILIA GRAPH software programs (Grimm, 1991). Pollen zones were identified with the aid of CONISS (Grimm, 1987).

#### 3.4. Loss on ignition

Sub-samples of 1 cm<sup>3</sup> were taken at every alternate 1 cm interval to pollen sub-samples and additional sub-samples of 1 cm<sup>3</sup> were taken at 1 cm intervals at points of interest for TAS1606SC2. Loss on ignition analysis was performed to determine organic



content (weight loss following 550 °C burn), carbonate content (weight loss following 950 °C burn) and siliciclastic content (residual), after drying overnight at 60 °C to determine water content (Heiri et al., 2001).

### 3.5. Statistical analyses methods

#### 3.5.1. Detrended correspondence analysis

Ordination analysis using Detrended Correspondence Analysis (DCA) (Hill and Gauch, 1980) was employed on the fossil pollen data of each core on: (1) a dataset of pollen percentages based on a terrestrial pollen sum; and (2) a dataset of pollen and spore percentages based on all pollen and spores using DECORANA in PC-ORD 6.08 (McCune, 1999). Correlations between pollen and spore taxa and the DCA ordination axes are displayed in the ordination biplot that have an  $R^2$  value of 0.3 or above. Variance explained by each axis was determined by dividing the axis eigenvalue (variation represented by the axis in the ordination space) by the total variance in the multivariate data (i.e. the total inertia) and converting into a proportion (sensu McCune, 1999).

#### 3.5.2. Sequential *t*-test analysis of regime shifts (STARS)

A sequential *t*-test algorithm (STARS) was used to identify significant shifts in the DCA axes. STARS compares the differences between mean values of a moving window of values in a time-series using sequential *t*-tests. A regime shift is identified when two segments are statistically different, thus, allowing the identification of the timing and magnitude of regime shifts (statistically significant changes in the mean values of the time-series data) (Rodionov 2004; Rodionov and Overland, 2005). STARS (v. 3.2) (National Oceanic and Atmospheric Administration, 2006) was applied to the two pollen DCA datasets (TAS1602: DCA axis 1 and TAS1606SC2: DCA axis 2). Significant regime shifts in the datasets were identified as shifts in the mean values with a significant level of 0.05 and a sample window of 10 samples.

#### 3.5.3. Rate of change analysis

We use rate of change analysis to understand how variable the ecosystem is at any point in time. Rate of change quantifies the rate of ecological change (per unit time) by quantifying the multivariate distances between adjacent samples interpolated to represent event time intervals). Rate of change analysis was performed on the proxy data (pollen and LOI) from each core following modified methods of Bennett and Humphry (1995) and Dodson and Mooney (2002). Charcoal was excluded from this analysis as we assumed that charcoal was an extrinsic factor (Williams et al., 2011). To satisfy the requirements of rate of change analysis, the proxy records were interpolated to the median age resolution of each core in PSIMPOLL 4.27 (Bennet, 2007) using the chi-squared ( $\chi^2$ ) dissimilarity coefficient to calculate dissimilarity. We interpret increased rate of change values as reflecting more a variable ecosystem, while decreased rate of change values are inferred to represent lower ecosystem variability (i.e. a more stable environment).

#### 3.5.4. Human population estimates

Due to the low-resolution archaeological records of the sites within the study region (Jones, 1965, 1966, 1967), archaeological sequences and artefact data could not be compared at the same scale as the high-resolution palaeoecological record. To overcome this problem, time-series radiocarbon data was used as a proxy for human activity and prehistoric population (sensu Williams, 2013). Radiocarbon data were derived from the AustArch3 database (Williams et al., 2014), selecting archaeological sites within northwest Tasmania (the 'King' and 'Tasmanian Northern Slopes'

biogeographic regions) (Table 2). Radiocarbon data was calibrated per SHCal13 (Hogg et al., 2013) using OxCal (v. 4.2) (Risbey et al., 2009) to obtain a median value for each radiocarbon date (within 95.4% confidence). Calibrated dates were then 'data binned' into 500-year intervals based on the median value. Open sites within the dataset were corrected for taphonomic bias following the model outlined by Surovell et al. (2009) and applied following the methods in Williams (2013). To estimate palaeo-population levels, the annual percentage growth rate (GR<sub>ANN</sub>) equation was applied to the resulting dataset (sensu Williams, 2013).

## 4. Results

### 4.1. Core description and chronology

#### 4.1.1. Blue bog

A 150 cm core was recovered from the centre of the swamp (TAS1602). Further penetration was impossible, with retrieval of the basal material precluded by the d-section design (protruding spike that facilitates penetration but does not allow recovery). The core consisted of broadly homogenous peaty sediment that was mostly dark brown in colour. The basal 23 cm of sediment was well-humified peat (2.5Y 2.5/1). Between 104 and 127 cm, alternations between layers of peat with herbaceous plant material (10 YR 4/4) and well-humified peat (2.5Y 2.5/1) were evident. The middle section, between 70 and 104 cm was characterised by well-humified peat (2.5Y 2.5/1). The top 70 cm alternated between layers of peat with herbaceous plant material (10 YR 4/4) and well-humified peat (2.5Y 2.5/1). Radiometric analyses were performed on TAS1602 (Table 1). A radiocarbon age of 3721 cal yr BP was obtained at a depth of 142 cm. The Bayesian age-depth model reveals a median sediment accumulation rate of 29 yr cm<sup>-1</sup> (Fig. 2a).

#### 4.1.2. Rebecca lagoon

Two short cores were recovered from the general centre of the lagoon (TAS1606SC1 [105 cm] and TAS1606SC2 [115 cm]), however only TAS1606SC2 was used in this study as it captured more of the sediment. Further penetration what halted by compact sands. The basal 35 cm of sediment was quartz sand (2.5Y 3/2). Overlying the sand, between 22 and 80 cm, was peat interspersed with dark humus sediment (2.5Y 2.5/1) that contained some herbaceous and woody plant fragments and a few small, thin, horizontal roots. Another section of quartz sand (2.5Y 3/2) followed between 19 and 22 cm. The top 19 cm comprised of consolidated, dark humus (2.5Y 2.5/1). Radiometric analyses were performed on TAS1606SC2 (Table 1). A maximum radiocarbon age of 5153 cal yr BP was obtained at a depth of 108 cm. The BACON age-depth model reveals accumulation rates at a median rate of 24 yr cm<sup>-1</sup> (Fig. 2b).

### 4.2. Macroscopic charcoal

#### 4.2.1. Blue Bog

Macroscopic CHAR values gradually increase from ca. 4300 cal yr BP, with a large peak ca. 3000 cal yr BP. Between 3000 and 1700 cal yr BP, CHAR values are generally low with some small peaks at ca. 2600 and 1900 cal yr BP. After 1700 cal yr BP the CHAR record becomes highly variable with distinct peaks and troughs (Fig. 3a).

#### 4.2.2. Rebecca Lagoon

Macroscopic CHAR values are generally low until a steep increase ca. 2300 cal yr BP, with fluctuating peaks and troughs thereafter. Slight peaks occur ca. 4700 and between 2700 and 2600 cal yr BP with distinct peaks between 2300 and 1900, 1500–1050 and 900–500 cal yr BP (Fig. 3b).

**Table 1**  
Radiocarbon dating results for Blue Bog (TAS1602) and Rebecca Lagoon (TAS1606SC2) cores. Upper and lower ranges are based on 2-sigma error ranges. Calibrations are based on the Southern Hemisphere calibration curve of Hogg et al. (2013) using OxCal (v. 4.2) (Risbey et al., 2009).

Laboratory code	Core code	Depth	Sample type	Fraction of modern		Radiocarbon		Calibrated ages		
						<sup>14</sup> C yr. BP)		(cal yr BP)		
				pMC	1σ error	BP	1σ error	Weighted mean	Lower range	Upper range
D-AMS 016568	TAS1602	27–28 cm	Sediment	89.9	0.39	856	35	673	529	764
D-AMS 016569	TAS1602	64–65 cm	Sediment	88	0.47	1023	43	1053	867	1270
D-AMS 016581	TAS1602	103–104 cm	Sediment	78	0.31	1996	32	1886	1722	2096
D-AMS 016570	TAS1602	141–142 cm	Sediment	62.7	0.37	3745	47	3721	2900	4113
D-AMS 016583	TAS1606SC2	17.5–18 cm	Plant matter	84.5	0.29	1351	28	1031	908	1169
D-AMS 016575	TAS1606SC2	34–34.5 cm	Sediment	81.3	0.4	1668	40	1553	1412	1708
D-AMS 016576	TAS1606SC2	42.5–43 cm	Sediment	77.4	0.25	2058	26	1912	1746	2017
D-AMS 016577	TAS1606SC2	61.5–62 cm	Sediment	76.2	0.35	2181	37	2189	2061	2311
D-AMS 016579	TAS1606SC2	80.5–81 cm	Sediment	71.7	0.29	2671	32	2707	2504	2882
D-AMS 016580	TAS1606SC2	107.5–108 cm	Sediment	56	0.2	4663	29	5153	4669	5497

**Table 2**

Archaeological sites used in the calculation of annual percentage human population growth estimates. Data sourced from Williams et al. (2014) AustArch3 database.

Site	Site Type	Lat (°S)	Long (°E)	IBRA Region	Material dated	14C age and error	Calibrated age (median)	Bin age
Muttonbird Midden	Midden	40.33	144.73	King	Charcoal	420 ± 70	420	500
Rocky Cape North	Rockshelter	40.86	145.51	Tasmanian Northern Slopes	Charcoal	450 ± 105	438	500
Stockyard Site, HI	Midden	40.52	144.76	King	Charcoal	760 ± 70	661	1000
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	840 ± 100	731	1000
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	840 ± 100	731	1000
Rookery Rockshelter	Rockshelter	40.33	144.73	King	Charcoal	870 ± 70	748	1000
Little Duck Bay	Midden	40.80	145.10	King	Charcoal	900 ± 90	781	1000
Cava Bay Cave, KI	Rockshelter	40.34	144.45	King	Charcoal	990 ± 90	852	1000
Little Duck Bay	Midden	40.80	145.10	King	Charcoal	1000 ± 60	856	1000
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	1070 ± 110	934	1000
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	1230 ± 80	1104	1500
West Point	Midden	40.95	144.63	King	Charcoal	1330 ± 80	1197	1500
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	1350 ± 200	1212	1500
Rookery Rockshelter	Rockshelter	40.33	144.73	King	Charcoal	1370 ± 70	1231	1500
Flat Topped Bluff	Midden	40.73	144.69	King	Wood charcoal	1500 ± 150	1372	1500
Arthur River	Midden	41.05	144.67	King	Charcoal	1560 ± 70	1413	1500
Muttonbird Midden	Midden	40.33	144.73	King	Charcoal	1610 ± 160	1486	1500
West Point	Midden	40.95	144.63	King	Charcoal	1850 ± 80	1737	2000
Nettle Bay	Midden	40.95	144.63	King	Wood charcoal	2350 ± 150	2351	2500
Rocky Cape North	Rockshelter	40.86	145.51	Tasmanian Northern Slopes	Charcoal	2420 ± 60	2443	2500
Cave Bay Cave, KI	Rockshelter	40.34	144.45	King	Charcoal	2580 ± 70	2594	3000
Marawah	Midden	40.95	144.63	King	Wood charcoal	2600 ± 120	2613	3000
Cave Bay Cave, KI	Rockshelter	40.34	144.45	King	Charcoal	3330 ± 100	3525	3500
Rocky Cape North	Rockshelter	40.86	145.51	Tasmanian Northern Slopes	Charcoal	3430 ± 95	3641	3500
Rocky Cape South	Rockshelter	40.86	145.51	Tasmanian Northern Slopes	Charcoal	3795 ± 100	4125	4000
Cave Bay Cave, KI	Rockshelter	40.34	144.45	King	Charcoal	3960 ± 110	4349	4000
Arthur River Bridge 1	Midden	41.05	144.67	King	Charcoal	4050 ± 240	4485	4500
Mt. Cameron West	Midden	40.86	144.71	King	Charcoal	4260 ± 360	4773	5000
Rookery Rockshelter	Rockshelter	40.33	144.73	Tasmanian Northern Slopes	Charcoal	5075 ± 250	5228	5500
Rocky Cape South	Rockshelter	40.86	145.51	Tasmanian Northern Slopes	Charcoal	5425 ± 135	5793	6000

### 4.3. Palynology

#### 4.3.1. Blue Bog

The pollen diagram for the Blue Bog core (TAS1602) is presented in Fig. 4. Three main pollen zones (zone 1: 4314–2000 cal yr BP [150–108 cm], zone 2: 2000–710 cal yr BP [108–30 cm] and zone 3: 710 cal yr BP–present [30–0 cm]) and two subzones were identified.

Zone 1 is divided into two subzones based on CONISS (numbers in parentheses are maximum values). Subzone 1a (4314–3200 cal yr BP) is dominated by *Melaleuca* spp. (56%), *Eucalyptus* spp. (38%) and *Leptospermum* spp. (26%). The aquatic assemblage is dominated by *Lemna*-type (39%) and no algae were present. Microscopic CHAR is generally low throughout the subzone. Subzone 1b (3200–2000 cal yr BP) is dominated by *Melaleuca* (51%), *Leptospermum* spp. (40%) and *Eucalyptus* spp. (40%). *Lemna*-type (13%) sharply reduces, and remains low, while *Sphagnum* spp. (5%) increases and remains constant throughout the subzone. The colonial green algae

*Botryococcus* spp. only appears at the beginning and the end of the subzone. There are two distinct peaks in microscopic CHAR at ca. 3700 and 2300 cal yr BP.

Zone 2 (2000–710 cal yr BP) is characterised by fluctuating levels of *Melaleuca* spp. (55%) and *Leptospermum* spp. (41%). *Eucalyptus* spp. (45%) remains present throughout the zone while *Dodonaea* spp. (26%) sharply increases towards the end of the zone. The aquatic assemblage is abundant in *Lemna*-type (31%). Microscopic CHAR is highly variable with several distinct peaks throughout this zone, particularly between 800 and 1000 cal yr BP.

In zone 3 (710 cal yr BP–present), *Dodonaea* spp. (19%) and Poaceae (11%) increase. *Melaleuca* spp. (30%) and *Eucalyptus* spp. (23%) decline as *Leptospermum* spp. (40%) and *Leptospermum/Baekea*-type (8%) become the dominant myrtaceous taxa in this zone. Both the colonial green algae, *Botryococcus* spp., and the aquatic plant, *Lemna*-type (58%), become prevalent throughout this zone. Microscopic CHAR sharply declines at the start of this zone and

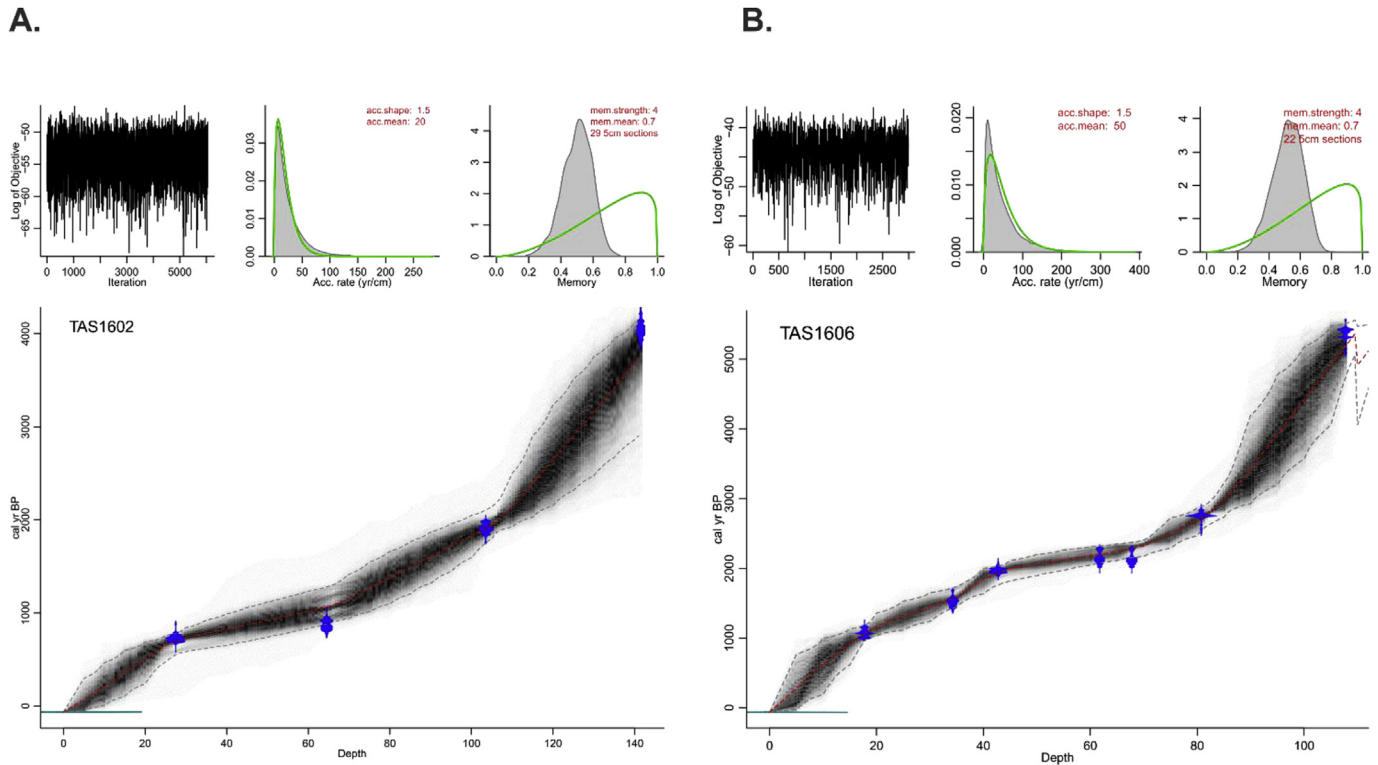


Fig. 2. Age-depth model for (A.) TAS1602 and (B.) Rebecca Lagoon core (TAS1606SC2) based on Bayesian age-depth model performed with Bacon (Blaauw and Christen, 2011).

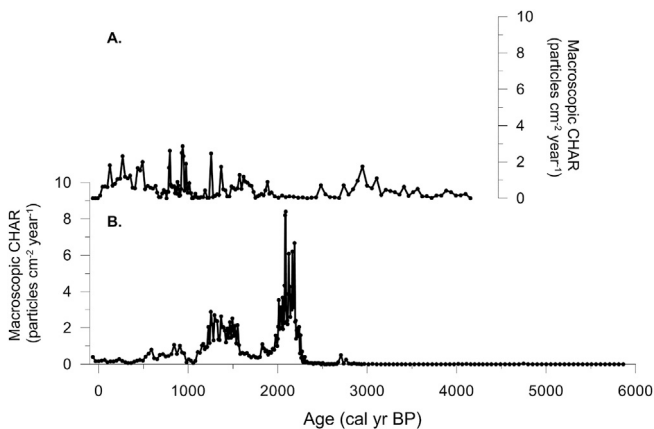


Fig. 3. Macroscopic CHAR data for (A.) TAS1602 and (B.) TAS1606SC2.

remains low throughout. The presence of Asteraceae *Liguliflorae*-type and *Plantago* spp. in the uppermost depths (ca. 70 cal yr BP) suggests that this represents British invasion/presence.

#### 4.3.2. Rebecca Lagoon

The pollen diagram for the Rebecca Lagoon core (TAS1606SC2) is presented in Fig. 5. Five main pollen zones (zone 1: 5812–4100 cal yr BP [114–96 cm], zone 2: 4100–2650 cal yr BP [96–80 cm], zone 3: 2650–1880 cal yr BP [80–41 cm], zone 4: 1880–750 cal yr BP [41–13 cm] and zone 5: 750 cal yr BP–present [13–0 cm]) were identified.

Zone 1 (5812–4100 cal yr BP) is dominated by *Selaginella ulignosa* (23%), *Sprengelia incarnata* (13%) and *Amperea xiphocladus* (12%). *Leptospermum* spp. (12%) is also consistent. There are low percentages of sclerophyllous vegetation and aquatic plants with higher percentages of ferns. The algae *Zygnema* spp. is highly

abundant (83%). Microscopic CHAR is low throughout this zone.

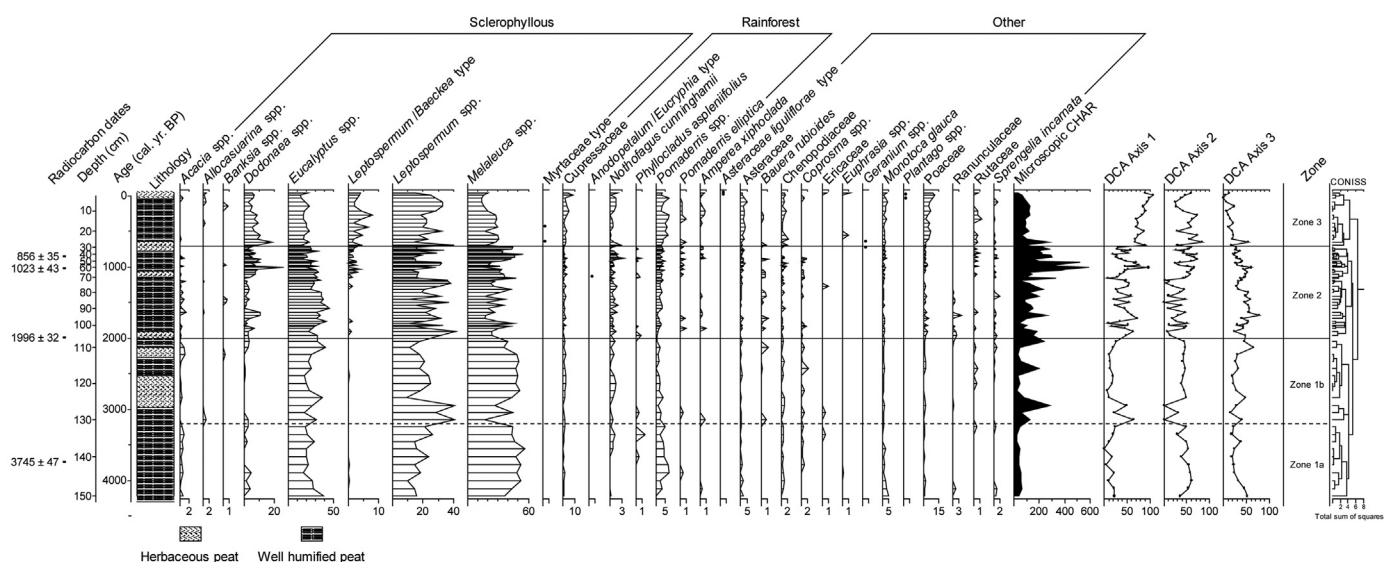
Zone 2 (4100–2650 cal yr BP) exhibits a number of compositional changes. *S. incarnata* (7%) and *A. xiphocladus* (2%) significantly decrease and *S. ulignosa* (20%) steadily declines in this zone. *Zygnema* spp. (19%) sharply declines and is absent thereafter. Both *Leptospermum* spp. (24%) and *Melaleuca* spp. (12%) increase along with the presence of Asteraceae (20%) and Poaceae (10%) while microscopic CHAR remains low.

At the transition into zone 3 (2650–1880 cal yr BP), *Melaleuca* spp. (25%) sharply increases whereas *Leptospermum* spp. (23%) sharply declines – an increase in *Leptospermum* spp. in the latter part of this zone corresponds to a sharp decrease in *Melaleuca* spp. Regional vegetation such as *Nothofagus cunninghamii* (14%) and Chenopodiaceae (10%) are better represented. Aquatic taxa and algae appear at the transition of this zone and remain constant throughout. Microscopic CHAR remains low until a sharp increase ca. 2100 cal yr BP.

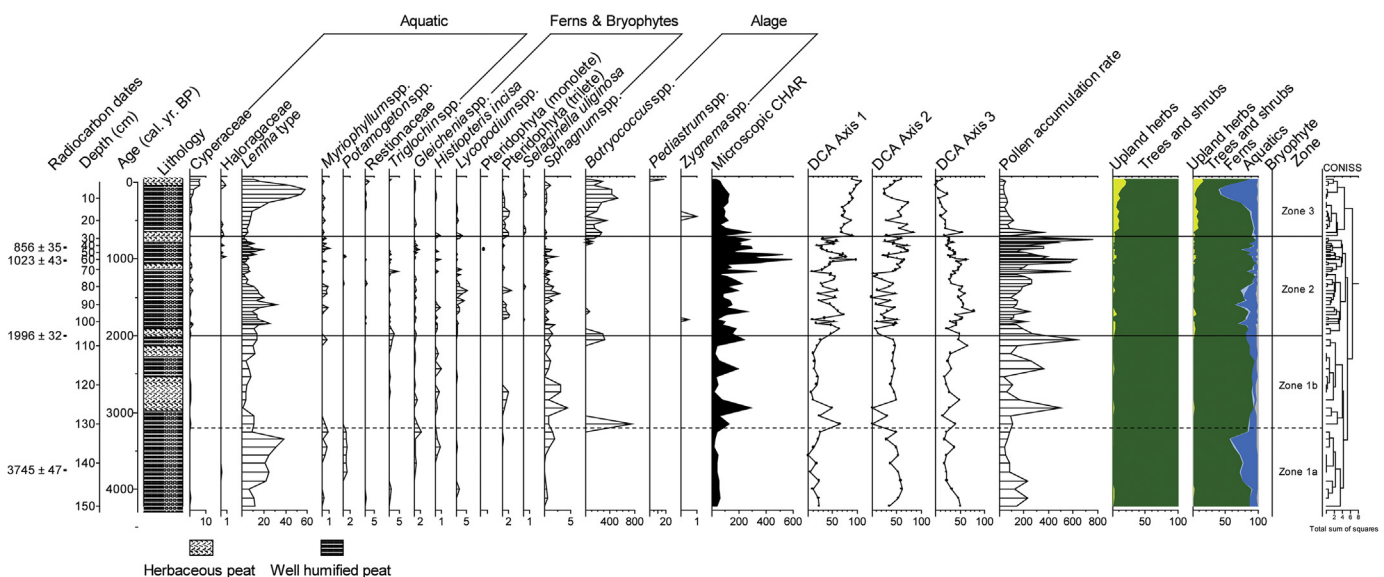
There are several peaks in microscopic CHAR throughout zone 4 (1880–750 cal yr BP), which correspond to vegetation shifts. *Melaleuca* spp. (20%) steadily declines to an overall low ca. 1300 cal yr BP; steadily increasing thereafter, whereas *Leptospermum* spp. (26%) exhibits the opposite trend with a peak ca. 1300 cal yr BP. Aquatic taxa *Triglochin* spp. (14%) and *Potamogeton* spp. (7%) become prominent and algal taxa *Botryococcus* spp. and *Pediastrum* spp. exhibit distinct peaks ca. 1350 cal yr BP.

The most recent period, zone 5 (750 cal yr BP–present), is marked by an increasing trend in *Melaleuca* spp. (29%) and a decreasing trend in *Leptospermum* spp. (18%). Aquatic taxa Cyperaceae (11%), Restionaceae (10%) and *Myriophyllum* spp. (7%) all increase while *Triglochin* spp. (8%) decreases. Microscopic CHAR remains consistently low. Algal (*Botryococcus* spp., *Pediastrum* spp. and *Zygnema* spp.) and heathland taxa (*A. xiphocladus*, *S. incarnata*, Rutaceae and *Euphrasia* spp.) are very minor or absent during this zone.

A.



B.



**Fig. 4.** Percentage pollen diagram for Blue Bog (TAS1602) showing (A.) terrestrial pollen taxa and (B.) aquatic, fern and algal taxa. Note the changes in x-scale. The y-axis is plotted according to age. Pollen zones are delineated by solid black lines, with subzones delineated by dashed black lines. The unit of measurement for microscopic CHAR (charcoal accumulation rate) is particles  $\text{cm}^{-2} \text{yr}^{-1}$ . Algal taxa are presented as accumulation rates.

#### 4.4. Loss on ignition

**Blue Bog:** LOI results are presented in Fig. 6a, with maximum values in parentheses. There is a general increase in organic matter over time (87%), except for a sustained decline between ca. 3400–2300 cal yr BP. Carbonates (15.4%) exhibit some distinct peaks throughout the record. **Rebecca Lagoon:** LOI results are presented in Fig. 6b with maximum values in parentheses. Organic content (7%) is consistently low between 6000 and 2800 cal yr BP. At ca. 2800 cal yr BP organic content (70%) begins to accumulate and increases sharply, remaining high throughout the remaining record.

Between ca. 1900–1200 cal yr BP there is a sharp increase in carbonate content (30%).

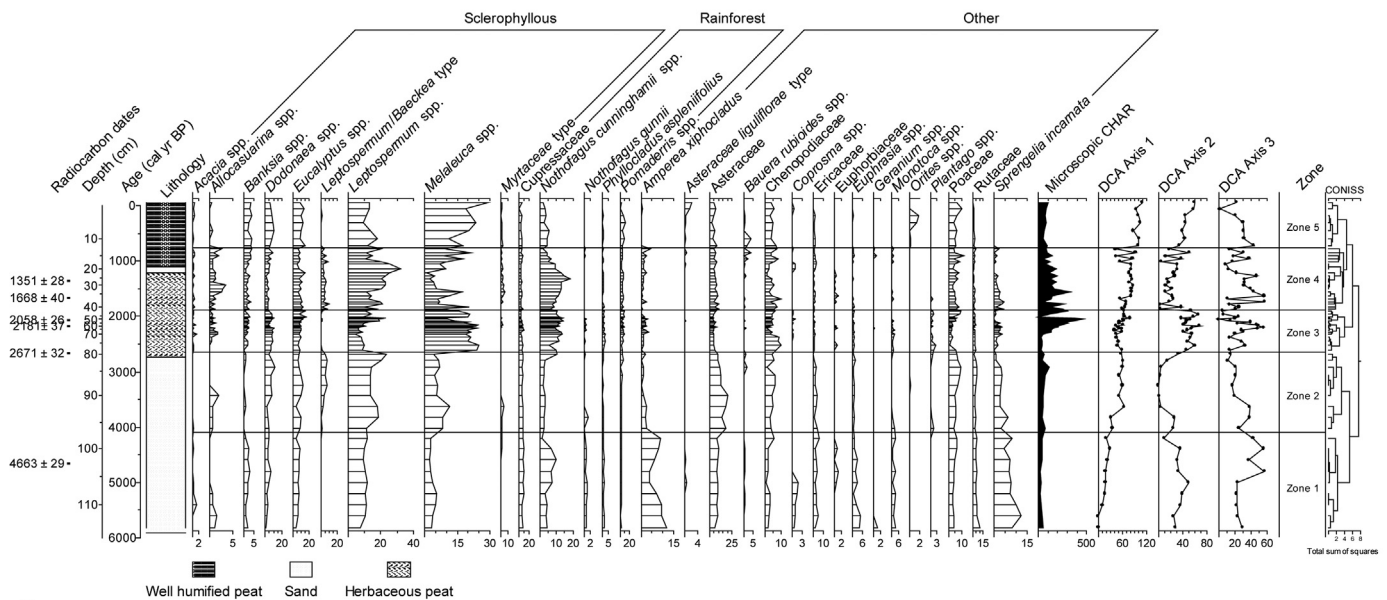
#### 4.5. Statistical analyses

##### 4.5.1. Detrended Correspondence Analysis

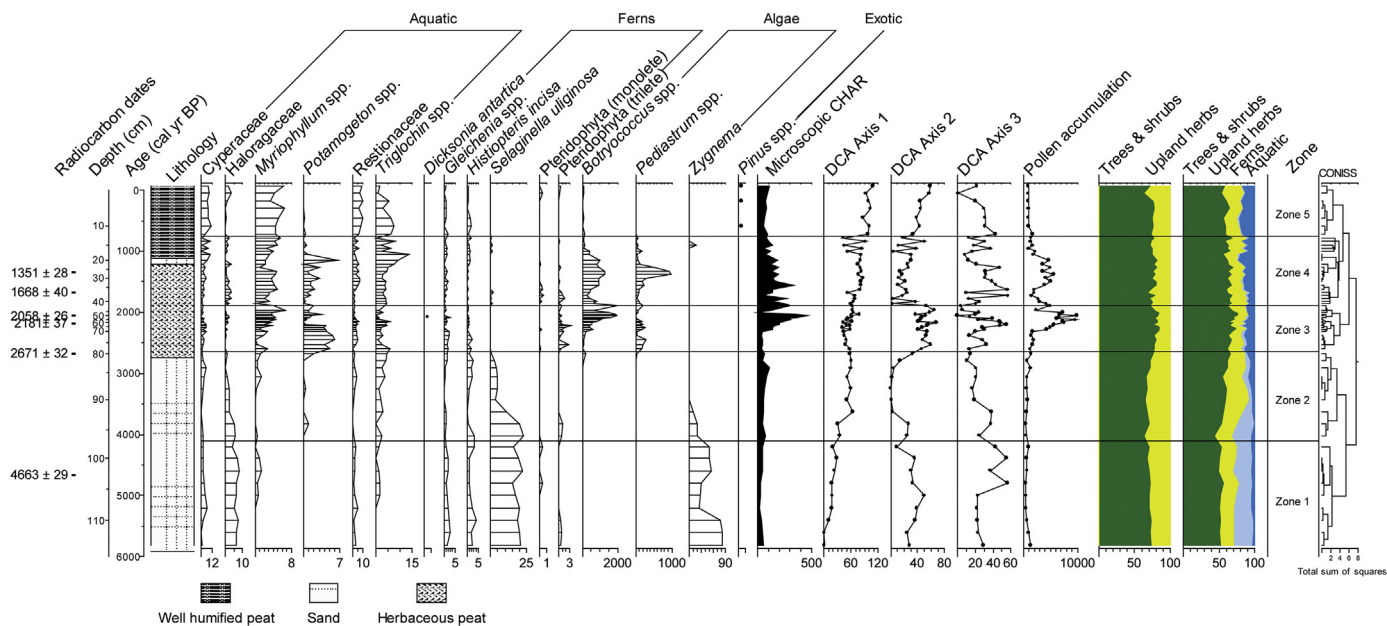
**Blue Bog:** DCA axis 1 explains 30.3% of the variance in the pollen dataset, with correlations with *Eucalyptus* spp. ( $R^2$  0.471), *Asteraceae* ( $R^2$  0.422) and *Dodonaea* spp. ( $R^2$  0.408). DCA axis 2 explains 12.7% of variance in the dataset and is weakly correlated with *Sprengelia incarnata* ( $R^2$  0.372), *Bauera rubiodes* ( $R^2$  0.319) and



A.



B.

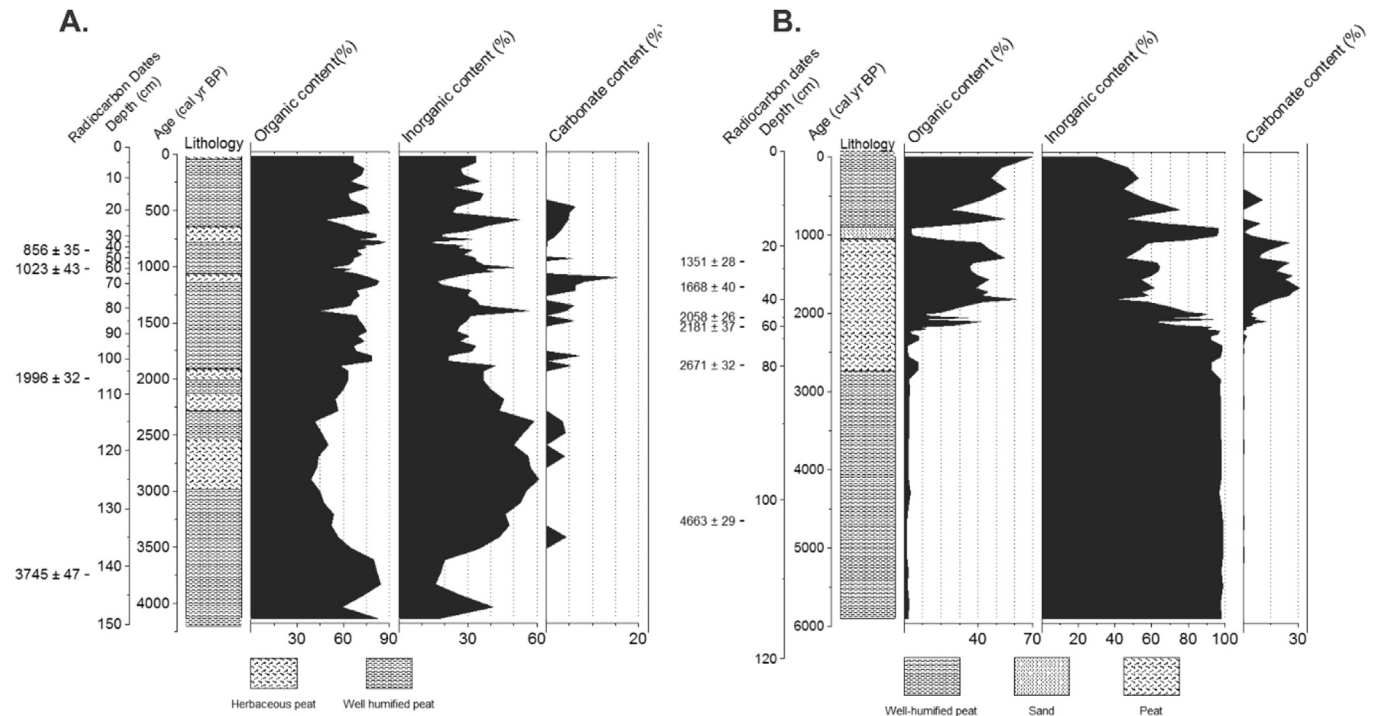


**Fig. 5.** Percentage pollen diagram for Rebecca Lagoon (TAS1606SC2) showing (A.) terrestrial pollen taxa and (B.) aquatic, fern and algal taxa. The y-axis is plotted according to age. Pollen zones are delineated by solid black lines, with subzones delineated by dashed black lines. The unit of measurement for microscopic CHAR (charcoal accumulation rate) is particles  $\text{cm}^{-2} \text{yr}^{-1}$ . Algal taxa are presented as accumulation rates.

*Leptospermum* spp. ( $R^2$  0.201). DCA axis 1 is shown in Fig. 8. **Rebecca Lagoon:** DCA axis 1 explains 33.3% of the variance in the Rebecca Lagoon pollen dataset, with strong correlations with *Sprengelia incarnata* ( $R^2$  0.708), *Amperea xiphocladus* ( $R^2$  0.623) and *Melaleuca* spp. ( $R^2$  0.663). DCA axis 2 explains 16.4% of the variance in the dataset and is correlated to *Phyllocladus aspleniifolius* ( $R^2$  0.441) and *Leptospermum* spp. ( $R^2$  0.497). DCA axis 1 is shown in Fig. 9 for the period of temporal overlap with Blue Bog only.

#### 4.5.2. Rate of change analysis

**Blue Bog:** There is a consistently low rate-of-change in the early part of the Blue Bog record until ca. 1950 cal yr BP, when there is a clear rise in rate-of-change values, which stay persistently high until ca. 900 cal yr BP. From ca. 900 cal yr BP onwards, rates of ecological change steadily decrease (Fig. 8). **Rebecca Lagoon:** There is a consistent low trend in rates of ecological change until ca. 3100 cal yr BP where rates of change begin to stepwise increase

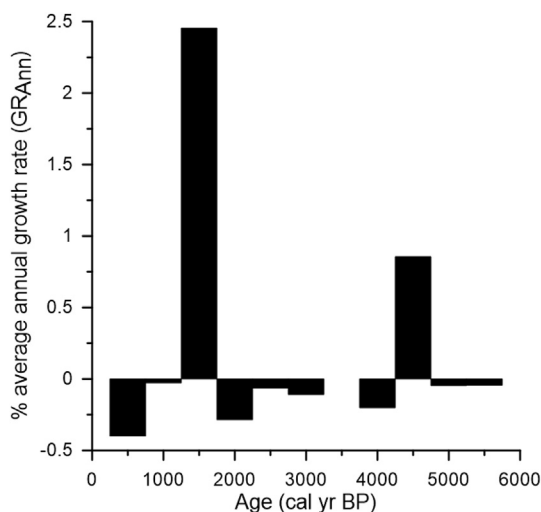


**Fig. 6.** Percentage LOI diagram showing selected results from (A.) Blue Bog (TAS1602) and (B.) Rebecca Lagoon (TASD1606SC2). Note the changes in x-scale. The y-axis is plotted according to age.

(Fig. 8) A large peak occurs ca. 2000 cal yr BP with a significant decreasing trend thereafter until another large peak occurs ca. 900 cal yr BP, followed by a substantial decrease (Fig. 9).

#### 4.5.3. Human population growth curve

The GR<sub>ANN</sub> analysis of the taphonomically corrected dataset indicates an average annual growth rate of 0.19% over the last 6000 cal yr BP, with a range between 2.45 and −0.40% (Fig. 7). There are only two positive average annual growth in population: one at ca. 4500 cal yr BP (0.85%) and one at ca. 1500 cal yr BP (2.45%)



**Fig. 7.** The entire Northwest Tasmanian percentage annual human population growth (GR<sub>ANN</sub>) dataset ( $n = 31$ ) [Table 4.3] calibrated and data-binned into 500-year time intervals, corrected for taphonomic loss and presented as a bar chart.

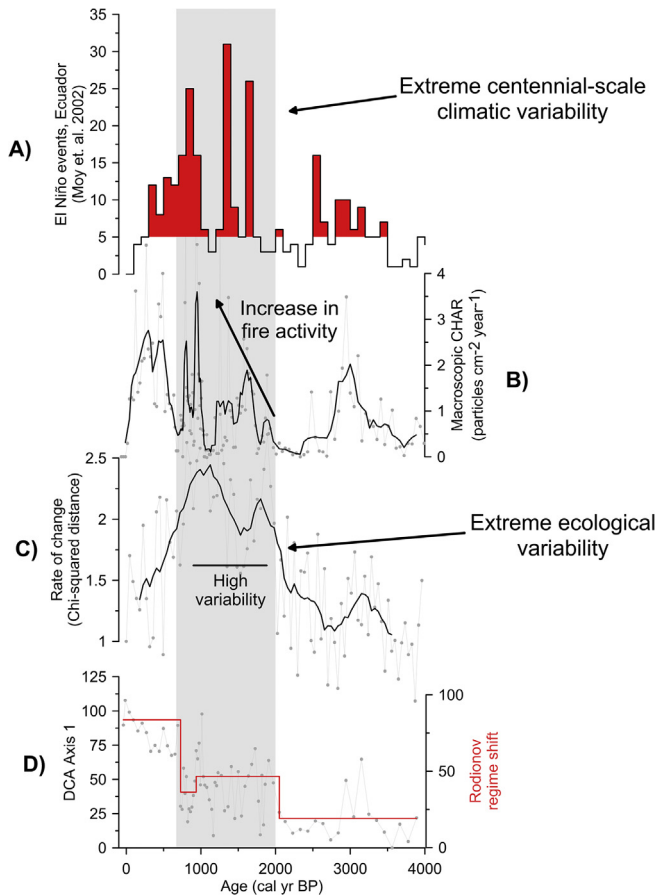
(Fig. 7). We note that while correcting for taphonomic bias, the total number of radiocarbon ages used in our analysis is low (31) and is, thus, prone to bias resulting from sampling effort and should be treated with caution. Nevertheless, given the lack of detailed and systematic analysis of archaeological material in this, paradoxically, archaeologically rich landscape, we contend that our GR<sub>ANN</sub> curve provides a best estimate of human population dynamics available at this time.

## 5. Discussion

### 5.1. Palaeoenvironmental reconstruction at Blue Bog

#### 5.1.1. Zone 1 (ca. 2000–4300 cal yr BP)

Organic accumulation at Blue Bog began ca. 4300 cal yr BP in an open water setting supporting *Myriophyllum* spp. and *Potamogeton* spp. and surrounded by *Melaleuca*-dominated swamp-forest (Fig. 4). An invasion of the site by *Sphagnum* and *Melaleuca* between 3500 and 2200 cal yrs BP is broadly contemporaneous (within chronological uncertainty) with an increase in *Sphagnum* across a number of sites in eastern Tasmania (Harle et al., 1993; Thomas, 1998; Jones et al., 2017), marked changes in bog vegetation in northern (Fletcher et al., 2014a, 2015a) and eastern Tasmania (Mackenzie and Moss, 2017) and with a spike in fire activity across western and southern Tasmania (Fletcher et al., 2014b, 2015b; Rees et al., 2015; Stahle et al., 2016; Beck et al., 2017; Mariani et al., 2017). The contemporaneity of these changes across Tasmania argues for a climatic driver. This period (ca. 3500 and 2200 cal yrs. BP) is associated with a phase of peak frequency occurrence of El Niño activity (Sandweiss et al., 2001; Moy et al., 2002; Riedinger et al., 2002) that would have brought about less precipitation and a drier climate over much of Tasmania (Figs. 8 and 10), and it is possible that the increase in *Sphagnum* reflects a local hydrological response to regional climatic change.



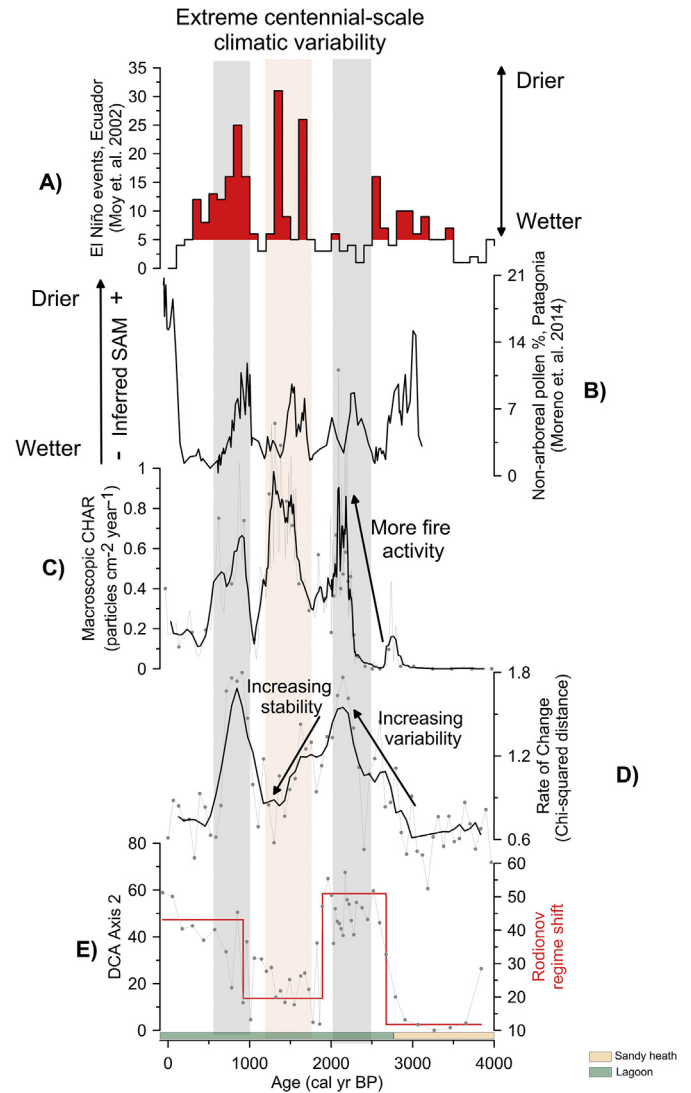
**Fig. 8.** Blue Bog summary diagram of extreme climatic variability evident in the (a) Laguna Pallcacocha number of El Niño events in 100-yr overlapping windows record (Moy et al., 2002), (b) an increase in fire activity (macroscopic CHAR record), (c) extreme environmental variability and (d) compositional shifts (solid red line) and vegetation turnover (grey line). The zone 2 period (2000–710 cal yr BP) is highlighted by the grey shading. A weighted average smoother (window-width = 3) (solid black line) was applied to macroscopic CHAR and rates of change to highlight the major trends in the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 5.1.2. Zone 2 (ca. 2000–710 cal yr BP)

This phase is marked by a highly variable vegetation system, evidenced by both the DCA trends, shifts in dominance between *Leptospermum* spp. and *Melaleuca* spp. and high rates of change that, together, indicate rapid shifts between swamp-forest and relatively drier scrub vegetation (Figs. 4 and 8). Moreover, the highly variable fire activity in concert with shifts between wetland dominance by *Lemna*-type (open water) and *Sphagnum* spp. (bog) (Fig. 4) suggest substantial hydrological variability through this phase (Gibson et al., 1987; Kirkpatrick and McKenny, 1999; Bowkett and Kirkpatrick, 2003). This period is marked by centennial-scale oscillations between phases of high and low El Niño frequency in the tropical east Pacific and it is likely that the changes recorded at Blue Bog reflect this ‘extreme’ climatic variability (Figs. 4 and 8) (Philander, 1983; Moy et al., 2002; Hill et al., 2009).

### 5.1.3. Zone 3 (ca. 710 cal yr BP to present)

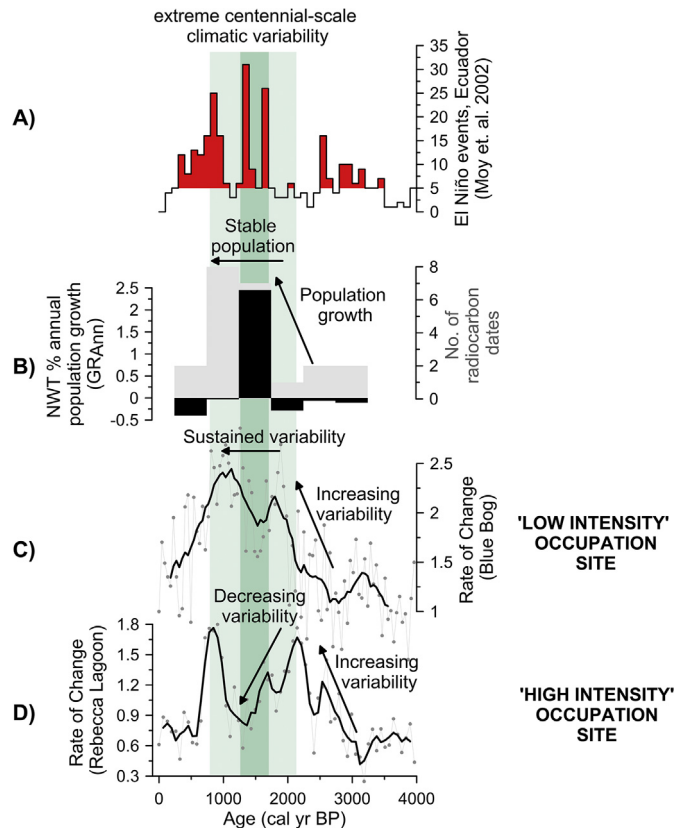
This phase represents a period of relatively stable dry conditions (between ca. 710 cal yr BP to present) resulting in reduced variability relative to the preceding phase (Fig. 8). A shift from *Melaleuca* to *Leptospermum* dominance suggests a localised lowering of the water table and the development of a drier forest type (Fig. 4) (Hope, 1999; Duncan, 2005; Kirkpatrick and Harris, 2005;



**Fig. 9.** Rebecca Lagoon summary (lagoon phase only) diagram of extreme climatic variability evident in the (a) Laguna Pallcacocha number of El Niño events in 100-yr overlapping windows record (Moy et al., 2002), (b) the Lago Cipreses non-arboreal pollen percentage (shrubs and herbs) record (inferred positive and negative SAM-like events (Mackenzie and Moss, 2017) (c) an increase in fire activity (macroscopic CHAR record), (d) environmental variability and (e) compositional shifts (solid red line) and vegetation turnover (grey line). The zone 2 period (2000–710 cal yr BP) is highlighted by the grey shading. A weighted average smoother (window-width = 3) (solid black line) was applied to macroscopic CHAR and rates of change to highlight the major trends in the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Kitchener and Harris, 2013) that is concomitant with evidence for the development of shallow stagnant water at the site (increases in *Lemna*-type and *Botryococcus* spp.) (sensu Fletcher et al., 2014a) (Fig. 4). This shift toward drier conditions occurs through a phase of increased El Niño frequency, suggesting that the local site responded to regional climatic change. Indeed, a drop in the frequency of El Niño events recorded in the tropical east Pacific corresponds to an increase in *Melaleuca* at the site, suggesting an increase in available moisture and a raising the water table that favoured this swamp forest taxon. (Fig. 4) (van de Geer et al., 1986, 1991; Colhoun, 1992). Finally, vegetation change associated with land use change following British invasion is indicated by an increase in exotic taxa, *Asteraceae* (*Liguliflorae*-type) and *Plantago* spp. (Lloyd and Kershaw, 1997; Romanin et al., 2016) (Fig. 4).





**Fig. 10.** Summary diagram of (a) the Laguna Palcacocho number of El Niño events in 100-yr overlapping windows record (Moy et al., 2002), (b) northwest Tasmanian (NWT) percentage (%) annual population growth (GRANN) and number of radiocarbon dated archaeological sites, (c) rate of change at Blue Bog (the unoccupied site) and (d) rate of change at Rebecca Lagoon (the occupied site). During a period of extreme climatic variability (dark green box) the two rate of change records between Blue Bog and Rebecca Lagoon diverge with sustained variability at Blue Bog and decreasing variability at Rebecca Lagoon at the same time human population and occupation (number of radiocarbon dated sites) increases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 5.2. Palaeoenvironmental reconstruction at Rebecca Lagoon

### 5.2.1. Zones 1 and 2 (ca. 5812–2680 cal yr BP)

Overall, this phase reflects a pre-lagoon phase and the formation of a coastal wetland, likely due to the damming of Rebecca Creek by the formation of the coastal dune complex that separates this site from the Southern Ocean. The vegetation at this time was dominated by sandy heath and wet heath species, *Amperea xiphoclada*, *Sprengelia incarnata*, *Selaginella uliginosa*, and *Gonocarpus* spp. (Simons, 1994; Kirkpatrick, 1999; Van Geel, 2002; Kirkpatrick and Harris, 2005; Holzinger et al., 2009; Kitchener and Harris, 2013; Bargmann and Kirkpatrick, 2015), while the prevalence of *Zygnema* spp., an epipelagic algae found in shallow stagnant pools or slow-flowing water, indicates that the site was likely a shallow pool or a periodically inundated area (possibly connected to Rebecca Creek to the north) (Figs. 5 and 9). The low values of *Leptospermum* spp. and *Melaleuca* spp. suggest the absence of fresh water swamp environments in the local area (Fig. 5). A decline in *Zygnema* spp. and *Gonocarpus* spp. at the expense of *Myriophyllum* spp. and *Triglochin* spp. after ca. 3200 cal yr BP indicates the formation of a freshwater lagoon at the site (Figs. 5 and 9) (Harle et al., 1999; Crawford et al., 2006). This establishment of deeper water was likely the result of increased dune formation and sea-level activity at this time (Cook, 1986; Head, 1987; Short, 1988; Sloss et al., 2007; Lewis et al., 2013).

### 5.2.2. Zone 3 (ca. 2680–1900 cal yr BP)

The establishment of a freshwater lagoon at the site was accompanied by an increase in *Melaleuca* spp., reflecting the formation of swamp forest around the lagoon (Fig. 9) (Gibson et al., 1987; Wells and Hickey, 2005; Kitchener and Harris, 2013) and a shift to a macrophyte community dominated by *Myriophyllum* spp., *Potamogeton* spp. and *Triglochin* spp., all taxa dependent on shallow to deep water. The establishment of the green algae *Pediastrum* spp. indicates open water conditions (Sigleo and Colhoun, 1981; Harle et al., 1999; van Geel, 2002; Crawford et al., 2006) (Figs. 5 and 9) that permitted the deposition of regional sources pollen from plants well-dispersed pollen types (e.g. the rainforest tree *Nothofagus cunninghamii*) in to the site. Fire activity increases between ca. 2680–1900 cal yr BP, reflecting an increase in combustible biomass in the local region. Interestingly, trends in fire activity at Rebecca Lagoon closely track shifts in the Southern Westerly Winds associated with SAM (Fig. 9), consistent with a reconstruction of precipitation variability derived from Rebecca Lagoon (Saunders et al., 2012). An increase in environmental variability (rate of change) peaks with a sharp increase in fire that is associated with more frequent positive SAM-like events, highlighting a strong link between vegetation, fire and climate at this site through this time (Fig. 9).

### 5.2.3. Zone 4 (ca. 1880–750 cal yr BP)

This period is marked by a clear decrease in ecosystem variability around Rebecca Lagoon (rate-of-change) in concert with a period of increased centennial-scale climatic variability – shifts between high and low frequency occurrence of El Niño events and a shift toward a more positive SAM-like climate state – and a sharp and sustained increase in fire activity (Fig. 9). A drier local environment is indicated by the shift in dominance from *Melaleuca* spp. to *Leptospermum* spp. (Kitchener and Harris, 2013) (Fig. 5). Increased carbonate content in the sediments at this time suggest an increase in evaporation (Botz and Borch, 1984) and a reduction in water level is indicated by the reduction of *Potamogeton* spp., a taxon that prefers deeper water (Hughes, 1990; Dieffenbacher-Krall and Halteman, 2000), at the expense of *Myriophyllum* spp. and the colonial green algae *Botryococcus* spp., which prefers shallow, stagnant water (Harle et al., 1999; van Geel, 2002; Crawford et al., 2006) (Fig. 5). The shift to a less variable (i.e. more stable) environment around Rebecca Lagoon in response to extreme climatic variability (increased El Niño activity and a trend in positive SAM-like events), increased moisture stress and higher fire activity (Fig. 9) contrasts with the previous interval in which there is a positive relationship between rate-of-change, increased climatic variability and increased fire activity (Fig. 9).

### 5.2.4. Zone 5 (ca. 750 cal yr BP–present)

A return of *Melaleuca* spp. and a reduction in regionally dispersed pollen taxa (e.g. *N. cunninghamii* and *Allocasuarina* spp.) indicates a less open waterbody and a shallow lagoon (Colhoun 1992; Fletcher and Thomas 2010) (Fig. 5). Slightly prior to the beginning of this zone, between ca. 1000 to 500 cal yr BP, there is a return to a positive relationship between increased fire activity, increased positive SAM-like events and increased environmental variability (Fig. 9). This further highlights a link at Rebecca Lagoon between climatic variability, fire, vegetation and depositional environment, that was decoupled in the previous phase (ca. 1880 and 750 cal yr BP) (Fig. 9). The presence of Asteraceae *Liguliflorae*-type throughout the record suggests that this is either the native species *Microseris scapigera* (yam-daisies) or *Actites megalocarpa* (dune thistle), both important food sources for people (Hiatt, 1968; Gott, 1982a) (Fig. 5).



### 5.3. Human-environment interactions in northwest Tasmania

Humans actively seek to create predictability in landscapes and this can be manifest as a reduction in the rate of environmental change (i.e. reduced environmental variability) in inhabited areas as human activity increases (e.g. Ren, 2000; Li et al., 2006; England et al., 2008; Bal et al., 2011). Whilst not indicating an absence of human influence, the absence of direct archaeological remains at the Blue Bog contrasts with direct evidence for human habitation and resource exploitation at and around Rebecca Lagoon. This contrast permits a comparison of the potential role of people in long-term local-scale environmental change between a site clearly and intensively utilised by people and a site that was (potentially) less intensively utilised. Our data indicates a decoupling between fire activity and environmental variability at the occupied site (Rebecca Lagoon) during the phase of radiocarbon inferred peak human population growth in northwest Tasmania between ca. 1700 to 900 cal yr BP (Figs. 8 and 10). Rebecca Lagoon is located adjacent to the only known Spongelite quarry in Tasmania, an important resource that was of substantial practical and economic importance for people living in this landscape. Indeed, Spongelite from Rebecca Lagoon has been found in archaeological deposits up to 40 km away, a spatial extent that is uncommon in the Tasmanian resource economy, implying that it was an important economic resource (Jones, 1965, 1966).

Rebecca Lagoon is one of the few fresh water sources along the northwest coast of Tasmania. The site has abundant biotic resources that, when coupled with a valuable source of spongelite and the local archaeological record (Jones, 1966, 1967, 1981; Stockton, 1981), indicates that the site was likely an important focal point for people in the northwest of Tasmania. We posit that the decoupling of environmental variability from increased fire activity and climatic variability during the phase of peak human population growth (between ca. 1700 to 900 cal yr BP) reflects the intentional management of the site through this phase (Fig. 10). The principal land management tool employed by Aboriginal Australians was fire, which was (and continues to be) applied skilfully and systematically to landscapes to attract game and to buffer against the catastrophic effects of uncontrolled wildfire on habitat structure, resource availability and biodiversity. Increased fluctuations in sedimentary charcoal in Tasmania and across eastern Australia, despite climatic variability and intensification of human activity and population during the mid-to late-Holocene, has been argued to be the result of a greater degree of adaption to the environment by people (Lourandos, 1980, 1983, 1988; Hiscock, 2002; Turney and Hobbs, 2006; Mooney et al., 2007; Black and Mooney, 2007; Black et al., 2008). Thus, we hypothesise that people occupying the northwest coast of Tasmania between ca. 1700 to 900 cal yr BP, in particular sites surrounding Rebecca Lagoon, adapted to highly variable climatic conditions by purposefully altering the landscape surrounding occupation sites with fire so as to create predictability in an increasingly unpredictable environment.

The period after ca. 900 cal yr BP is marked by a reduction in radiocarbon inferred population growth across northwest Tasmania, and a concomitant increase in environmental variability and a shift toward drier conditions at Rebecca Lagoon (Fig. 10). It is possible that people focused their activities elsewhere as the lagoon became too dry/stagnant, consistent with an increase in the importance of wetland taxa tolerant of brackish water (*Myriophyllum* spp. and *Restionaceae*) and the encroachment of swamp forest (increasing trend in *Melaleuca* spp.) (Fig. 5). The return of synchronicity of rate-of-change in trends between Blue Bog and Rebecca Lagoon further supports the notion of decreased influence of people around Rebecca Lagoon. It is important to note that the lack of detailed and systematic archaeological investigation record

at Rebecca Lagoon, and across northwest Tasmania, precludes an understanding of the change in resource exploitation through this phase. Noteworthy is the apparent late Holocene shift toward the manufacture of multi-purposed and more reliable tools through and a focusing on abundant resources such as Southern Elephant Seals (*Mirounga leonina*) (Jones, 1966, 1967, 1968, 1981), implying a dynamic economy through this time that might relate to the climatic and environmental changes we have reported here. An alternate explanation for the decoupling of fire activity and environmental variability at Rebecca Lagoon and not Blue Bog might lie in the intrinsic differences in how each wetland type (i.e. swamp-forest and dune-bound coastal lagoon) respond to high climatic variability and fire activity. However, the remarkable similarity in trends displayed at these sites outside of the phase of peak inferred human occupation between ca. 1700 to 900 cal yr BP argues against this explanation (Fig. 10).

## 6. Conclusion

We used a combination of pollen, charcoal and LOI data from cores taken in two northwest Tasmanian wetland sites to reconstruct past vegetation, fire histories and hydrological changes, enabling us to infer palaeoenvironmental patterns in northwest Tasmania during the mid-to late-Holocene. Assessing these records against the archaeological record, estimates of human population growth and climate change reveals insights into human-environment interactions in northwest Tasmania. Between ca. 1700 to 900 cal yr BP there is a breakdown in the persistent relationship between increases in charcoal and ecosystem variability at Rebecca Lagoon (the site with high occupation intensity). During this phase, environmental variability markedly drops at Rebecca Lagoon despite an increase in charcoal, while at Blue Bog (the low intensity occupation site), increasing charcoal at this time is associated with an increase in environmental variability. The decoupling of environmental variability and fire at Rebecca Lagoon occurs at a time of maximum population growth in the region and we contend that increased populations led to more intensive management of the landscape around Rebecca Lagoon at this time. Given the central tenet of human landscape management is to increase predictability in the environment, we argue that intensified management of the Rebecca Lagoon area drove a decrease in ecosystem variability (i.e. increased predictability). This study highlights the need for a reinvestigation into the archaeological record across northwest Tasmania and further high-resolution studies of wetlands across northwest Tasmania to further understand human-environment interactions in an area with a rich history of occupation.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.quascirev.2018.07.001>.

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